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Conduction of electricity through ice and snow

IV. Time variations of the current through a snow-ice sandwich and potential distribution in it in dependence on the electric treatment with unipolar potential

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With 12 figures in the text

In a preceding paper [5] various observed variations of the current and of the potential distribution in a snow-ice sandwich were described. Results of a more detailed investigation of some kinds of these variations will be presented here.

1. Experimental arrangement

1.1. *Snow-ice sandwich.*—The sandwich used was of the kind proposed in [5] and shown in Fig. 1. Only more care was devoted to prepare it. The electrical properties of ice and snow measured were besides other factors also influenced by the material of the electrodes used, as shown in [4]. Therefore the electrodes of the sandwich used in the present investigation were the same brass sieves used earlier [5], only chrome-plated, because it seemed that using such a kind of electrodes would be the simplest way by which undesirable disturbances caused by the material of the electrodes could be of a small scale. The sandwich was made of 4 chrome-plated sieves of 3.8 cm diameter with 3 slightly pressed snow discs (4.5 cm in diameter and 1 cm thick) between them. To avoid that the current might be conducted through snow directly from the leading wires soldered to the electrodes, the wires were coated with polystyrene insulation hoses. The intention was to use the sandwich during a protracted measuring series (it lasted about three weeks) and therefore care was to be taken to avoid sublimation of the snow. For this purpose the finished frozen sandwich was repeatedly sprayed with water and frozen so that at last the outside of the sandwich was completely covered with an ice crust. It seemed that by this treatment a comparatively definite sandwich was obtained. Later the sandwich was embedded in a paraffined carton box filled with snow for avoiding further variations.

It seems that a new branch of investigation of electrolytic conduction is being created, i.e. electrolytic conduction in solid water. Such a conception arose during the present investigation and it was encouraging to note that similar ideas are also reported by other authors [6]. It is obvious that only the first steps are indicated in this direction. The methodical side of the task seems to be of importance for the development of the investigation of the problems concerned, and the sandwich described might be regarded as a useful element for this purpose.

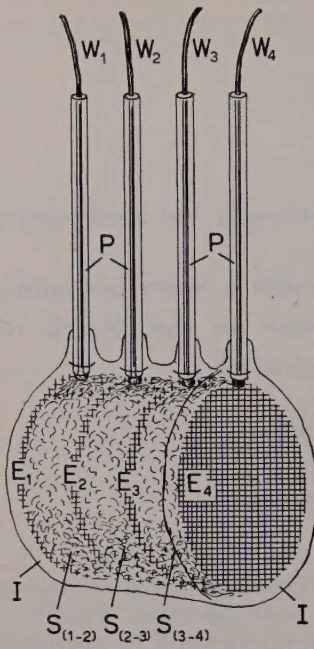

Fig. 1. The snow-ice sandwich. E_1, E_2, E_3, E_4, sieve-electrodes (chrome-plated brass); W_1, W_2, W_3, W_4, leading wires; P–P, polystyrene insulation hoses; S_{1-2}, S_{2-3}, S_{3-4}, snow disks; I, frozen ice cover.

1.2. *Device for recording the current.*—Some disturbances caused by alternating current components were observed in the current recording device used during our previous work [4]. Only partly was it possible to remove them by screening the amplifier and by earthing the inner metallic casing of the cold-box. Therefore the amplifier was rebuilt in a push-pull unit as shown in Fig. 2. For balancing the properties of the two valves used, adjustment of the heater voltages was resorted to as proposed already by Wynn-Williams and Brentano [2] and recently again by Aitchison [1]. The method for recording the current was that used during our previous work [4]. The current through the snow-ice sandwich was led through a resistor connected to the input terminals of the amplifier; the dropping of the potential on the resistor was amplified and recorded photographically with continually moving film by the CRO. The time marks were recorded on the film by short-circuiting the input resistor of one of the valves. However, some disturbances were observed by using this arrangement, especially when small time-scale variations occurred. Therefore for records of such variations, the intention was to record the time marks by using a separate incandescent lamp. The bias battery was used for adjustment of the working point of the amplifier. It was possible to record without difficulties the current between 0.1 μA and 1000 μA by changing the imput resistors of the amplifier.

1.3. *Electrometer for recording the potential difference between the electrodes.*—A bifilar Wulf electrometer was used for the visual recording of the potential distribution between the electrodes of the snow-ice sandwich. The connection of the electrodes to the other elements of the circuit is shown in Fig. 2.

1.4. *Procedure of recording.*—The intention was to investigate at first the long term variations. For this purpose at certain days during about 3 weeks the current and the potential distribution was recorded in the following way: at the beginning the levels were determined without changing anything in the arrangement, then the polarity of the potential applied to the sandwich was

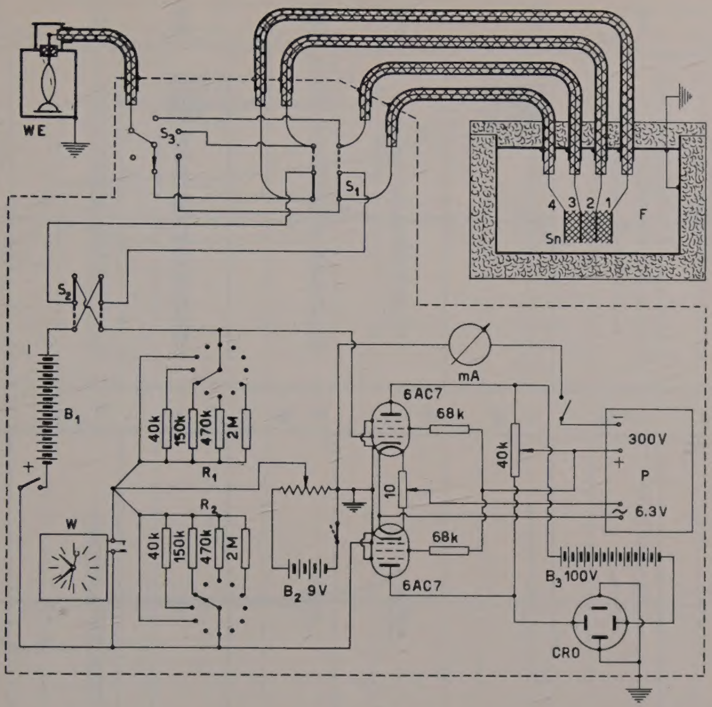

Fig. 2. Schematical diagram of the arrangement for measuring the distribution of the potential in a snow-ice sandwich and for recording the current through it. *F*, cold-box; *Sn*, snow-ice sandwich; *WE*, Wulf bifilar electromer; S_1, S_2, S_3, switches for commutation of the sandwich sections and of the polarity of electrical field applied; B_1, B_2, B_3, batteries; *W*, contact clockwork; *P*, power supply for the amplifier; *CRO*, cathode-ray oscillograph.

reversed and the variations of both—the current and the potential difference for each of the three sections—were recorded during 40 minutes. After finishing this series the polarity of the potential applied was changed again, i.e. it was the same as initially when the start levels were recorded, and a 40 minutes' series was recorded with this polarity. Series obtained in such a way (during 40 + 40 minutes) for both polarities of the potential applied and shown in Figs. 4–12 are denoted 1st series and are plotted with curves in heavy ink. After finishing these 1st series two similar series (during the following 40 + 40 minutes) were recorded. These series are denoted 2nd series and are plotted with fine-drawn curves. In one case only the 2nd series were not recorded and in two cases they were repeated only for one polarity of the potential applied. In all other cases two series for each polarity of the potential applied were thus obtained. Between the periods during which the recording was carried out a potential of one or the other polarity was applied to the sandwich except at the beginning, as also shown in Fig. 3. The potential applied was 170 volts, also during the recording.

It was evident that the variations under investigation depended on different factors, in the first place on the temperature. However, for recording a comparatively long time was necessary. Therefore the recording was carried out only at one temperature, $t = -5°C$ for obtaining firstly the general characteristic of the variations. By preliminary testing it was shown that the variations were of a large scale at temperatures near zero.

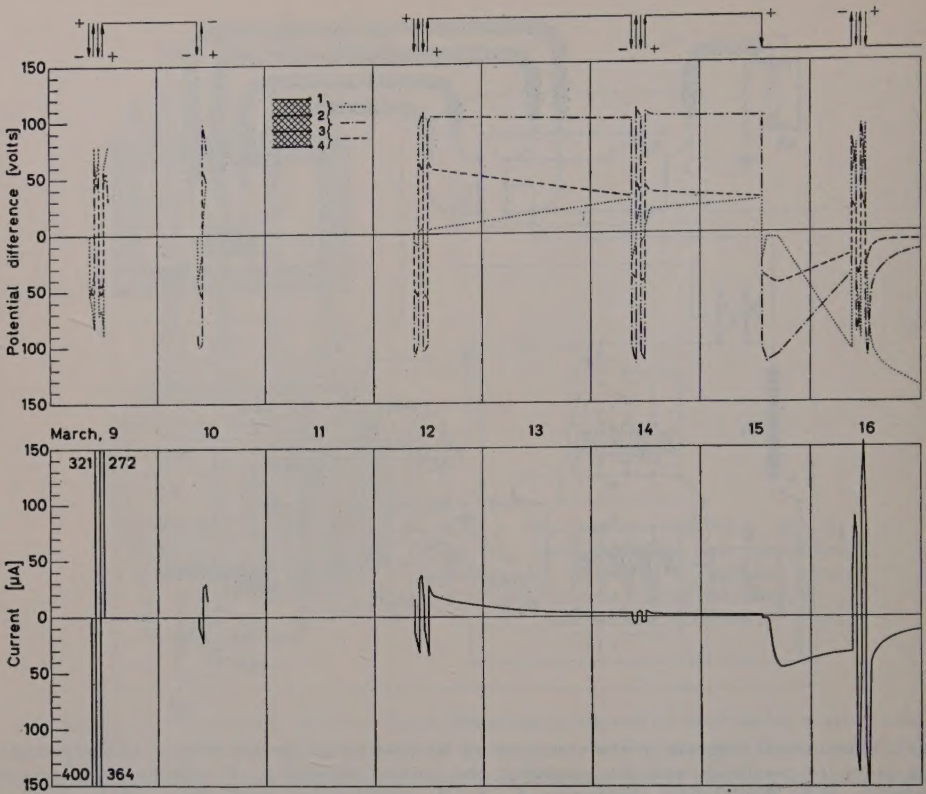

Fig. 3*a*. General survey of the variations of the potential distribution in a snow-ice sandwich and of the current through it during 15-day series.

2. Results

Results from one of the recorded long series which lasted 15 days will be discussed below. A general picture of the matter under consideration is given in Fig. 3, no details being indicated because of the time scale used. The individual series of 40 minutes' duration mentioned in 1.4 are shown in Figs. 4–12 in a suitable time scale.

As already mentioned, the intention of this work was to investigate the long time variations. As shown in the figures two kinds of these variations must be distinguished: (1) the *lasting variations* arising during a period of 1 day or even during a longer period at the beginning, and (2) *enforced* or *impressed variations* arising during some tens of minutes and characterized by great amplitudes. The lasting variations were observed when the sandwich was under tension of one or the other polarity during a long time period. The enforced variations were observed when the polarity of the potential applied during a long time period was reversed.

2.1. *Lasting variations.*—These variations are shown very clearly in Fig. 3, and as already mentioned they appeared when the sandwich was under tension of one polarity during a long time period (1 day or more). A certain distribution of the potential between the sections of the sandwich was obtained after such a treatment and it

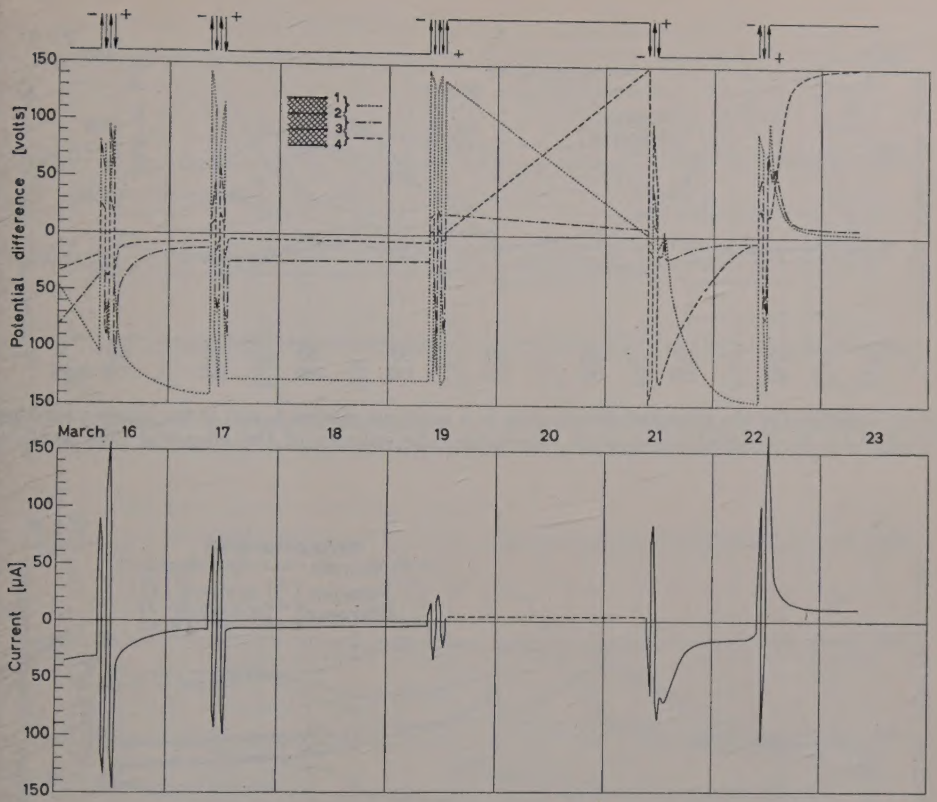

Fig. 3*b*. General survey of the variations of the potential distribution in a snow-ice sandwich and of the current through it during 15-day series.

was not easy to change this distribution by using an electric field of opposite direction. The formed distribution of the potential in the sandwich lasted for a comparatively long time. When an electrical field of the opposite direction was applied to the sandwich, the distribution of the potential was changed considerably only after a long time.

2.1.1. *Potential distribution in the sandwich.* For illustration of the phenomenon mentioned we will consider the trend of the potential distribution in the sandwich during the present long time series. The measurements were started on March 9. As shown in Fig. 3*a* and in greater detail in Fig. 4, potential differences in individual sections were comparatively equal. After finishing the 2 × (40 + 40) minutes' series with changed polarities a certain rearrangement of the potential distribution was observed: a higher potential difference was in the section (1–2), the next highest difference was in the section (3–4), and the smallest one in the middle section (2–3). A high current was recorded during these first series. During the following night the sandwich was under tension and on the following day the distribution of the potential was another one: the highest difference was in the middle section (2–3), the next highest one in (3–4), and the smallest one in (1–2) (Fig. 5). After finishing this series the sandwhich was short-circuited during 2 days. As shown later, the short-circuiting was without any important influence and therefore it was not surprising that by

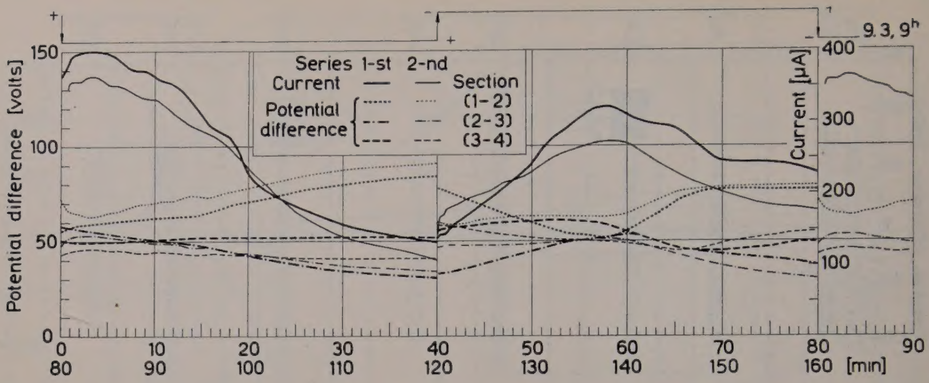

Fig. 4. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 4 × 40 minutes' series when alternating the polarity of the electrical field applied.

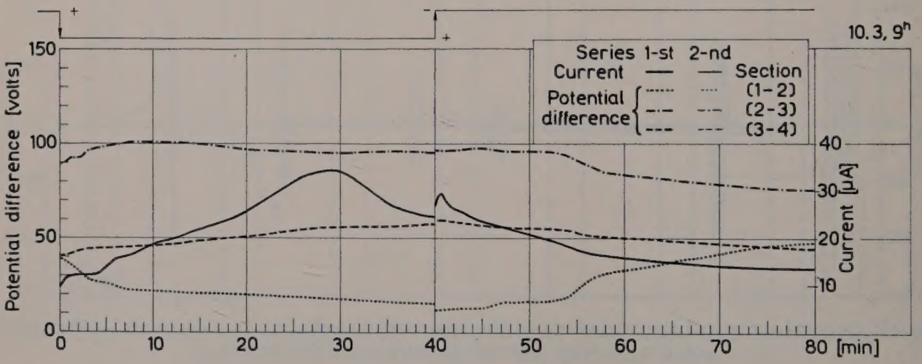

Fig. 5. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 2 × 40 minutes' series when alternating the polarity of the electrical field applied.

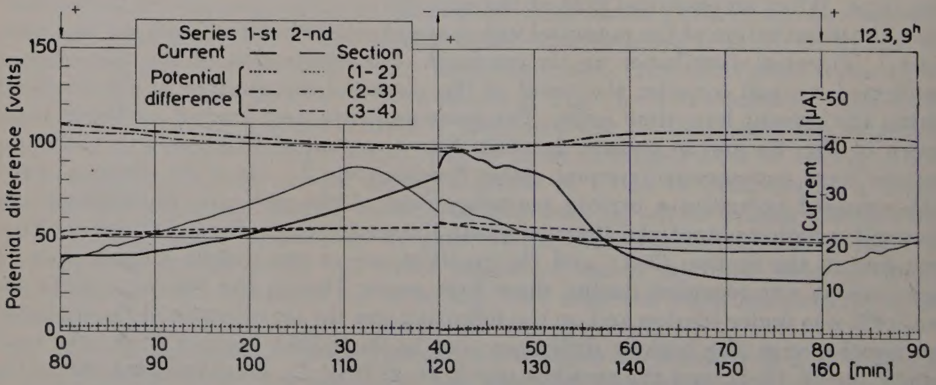

Fig. 6. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 4 × 40 minutes' series when alternating the polarity of the electrical field applied.

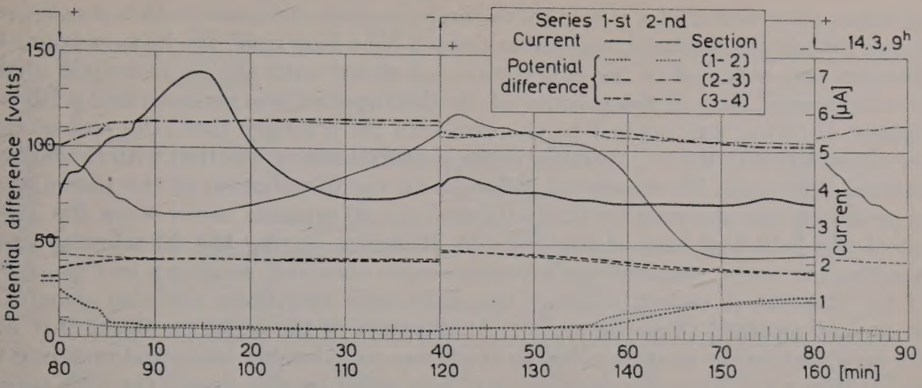

Fig. 7. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 4 × 40 minutes' series when alternating the polarity of the electrical field applied.

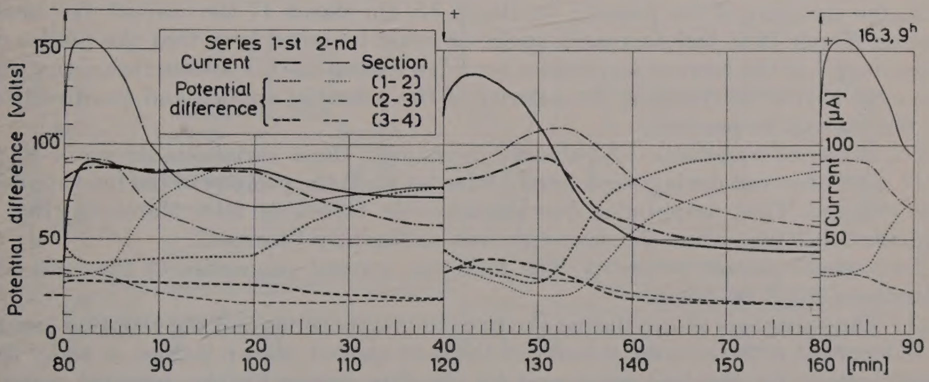

Fig. 8. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 4 × 40 minutes' series when alternating the polarity of the electrical field applied.

starting the series recorded on March 12 (Fig. 6) the potential distribution was similar to that recorded during the previous series with the highest difference in (2–3), a smaller in (3–4), and the smallest in (1–2). During the following two days the sandwich was under tension and on March 14 (Fig. 7) some changes were observed: the highest difference remained in (2–3), but in (3–4) it was smaller and in (1–2) it was increased. Therefore the field of the same direction was applied to the sandwich during the following night, and on March 15 the distribution of the potential remained the same as on the preceding day. During the following night the direction of the electrical field applied was changed to the opposite and considerable changes were observed on March 16 at the start of the series: the highest potential difference was in (1–2), the next highest in (2–3), and a small in (3–4) (Fig. 8). From this day a general change of the properties of the sandwich can be stated. By changing the polarity of the potential applied it was possible to turn the highest potential difference from one of the end sections (1–2) to the other (3–4) or in reversed direction. It seems that during the week of March 9–16 some kind of "formation" of the sandwich had taken place and that a new state in the properties of the sandwich had now been reached. When the sandwich was under tension for a long time, the highest potential difference was obtained in the end section connected with the (+) terminal of the potential source. Now, if the polarity of the field applied was reversed and a field of opposite direction was applied to the sandwich for a longer time, the end section now connected with the (+) terminal of the potential source was that with the highest potential difference. No remaining influence on the distribution of the potential in the sandwich was observed by the individual 4 × 40 minutes' series when the direction of the field had been changed twice. However, during the 40 minutes when recording the series, considerable variations were observed, as shown in Figs. 4–12.

2.1.2. *Current.* A certain trend of the large-scale variations was also shown for the current recorded (Figs. 3*a* and *b*). At the start of the series on March 9 it was very high, but on the next day (March 10) it was considerably lower and remained so also on March 12. When the sandwich was now under tension during the time period March 12–14 a new decrease of the current was observed on March 14, and on March 15 it had further decreased. Similar decreases of the current were observed on the days after March 16, when at the beginning the current was high, possibly in connection with the changing of the polarity on March 15. On March 17 the current was small and on March 19 it had decreased again. It could be noted here that the "order of magnitude" of the current amplitudes recorded during the 4 × 40 minutes' series was the same also when changing the polarity of the potential applied and the direction of the current respectively.

2.2. *Enforced variations.*—As already mentioned, these variations shown in Figs. 4–12 were observed during some tens of minutes when the polarity of the field applied was changed. Their amplitudes were considerable, especially after March 16 (Fig. 8 and the following) when the sandwich was sufficiently "formed".

2.2.1. *Some general properties.* The following general properties of the enforced variations could be noted:

(1) The variations shown during the first 40-minute series and the repeated series, both recorded with the same polarity of the field applied (shown in Figs. 4–12 by the heavy curves for the first series and by the thin curves for the repeated series), coincided during the first week when a series with reversed polarity was inserted between them, while after March 16 (when the sandwich was sufficiently formed) the shapes of the curves were different.

(2) A difference in the shape of the curves can be seen for the opposite polarities during one 40 + 40 minutes' series recorded.

(3) All the curves recorded after March 16 (after the "formation") have a similar shape, with the following characteristic properties:

(3.1) The current curve is a mirror image of the curve of the potential difference in the section with the highest potential difference during a given time period.

(3.2) A peculiar effect was observed during the second part of a 40 + 40 minutes' series when the potential applied was of the same polarity as before the starting of the series. During the first 4–5 minutes the trend of the potential was without any peculiarities, but after that the filament of the electrometer started to flicker in a range of some tens of volts and the flickering continued for 3–5 minutes as shown in Figs. 9, 10, and 12. Thereafter the filament of the electrometer continued to move without any jumps. It was not possible to investigate visually this phenomenon in greater detail; this must be carried out by using a recording instrument. The flickering was more pronounced for the section in which the highest potential difference was

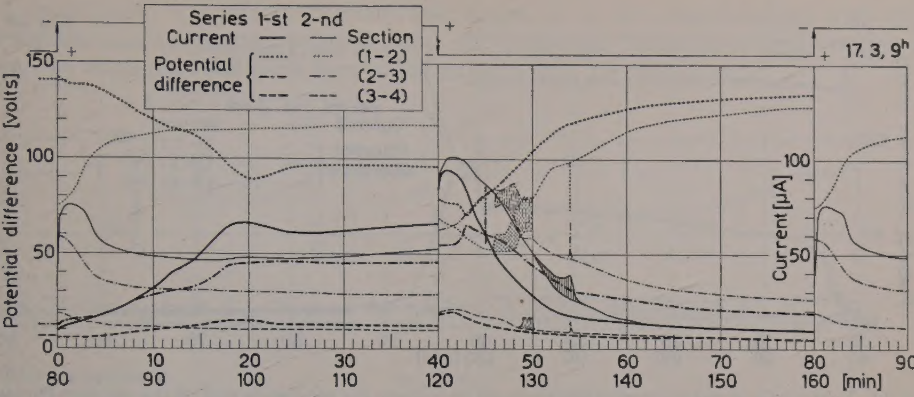

Fig. 9. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 4 × 40 minutes' series when alternating the polarity of the electrical field applied.

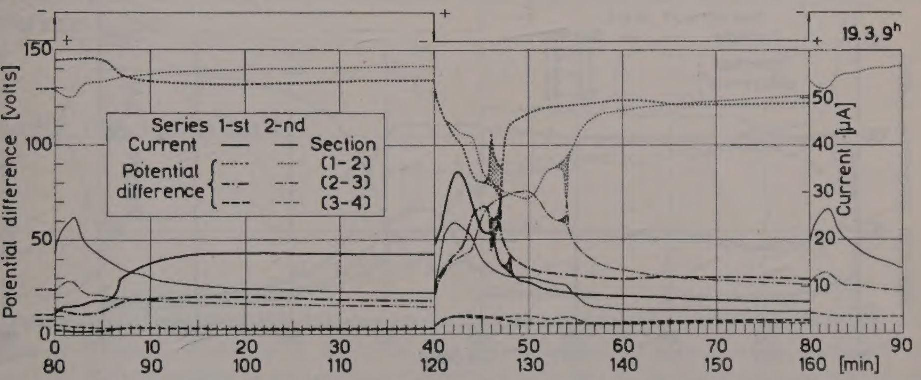

Fig. 10. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 4 × 40 minutes' series when alternating the polarity of the electrical field applied.

observed. A similar flickering was also seen for the current. This phenomenon must also be investigated more in detail by using a more appropriate recording arrangement.

2.2.2. *The mirror effect of the potential–time and current–time curves.* The potential difference curves for different sections are also mirror curves during a given period of time. The explanation of this is very simple. For the sake of simplicity we assume that only two sections, (1–2) and (2–3), are present. If a constant potential U is applied to the sandwich and the potential difference in each of the sections varies with time,

$$U_{12}(t) = -U_{23}(t) + U.$$

Another situation will be present if the current–time curve is a mirror image of the potential difference curve. In this case

$$U(t) = -A\,I(t) + B,$$

where $U(t)$ is the time function of the potential difference in one of the sections, $I(t)$ the current–time function, A and B constants depending on the units chosen. It is

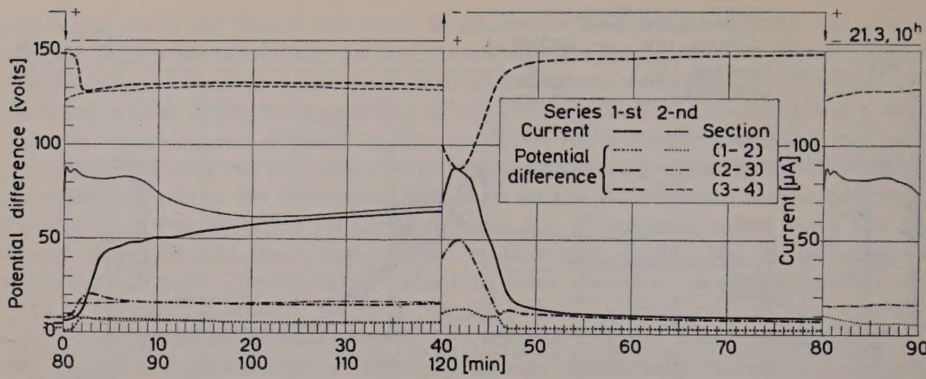

Fig. 11. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 3 × 40 minutes' series when alternating the polarity of the electrical field applied.

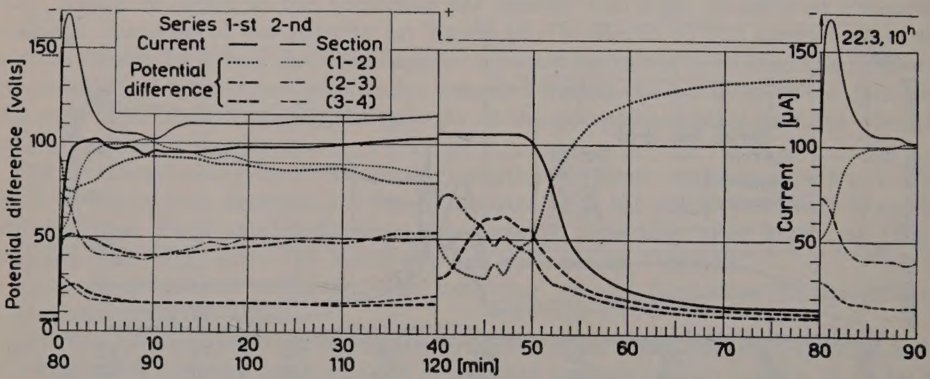

Fig. 12. Variations of the potential distribution in a snow-ice sandwich and of the current through it during 3 × 40 minutes' series when alternating the polarity of the electrical field applied.

of advantage to rewrite the equation in terms of the electrical field present, $E(t)$, and the current density $i(t)$:

$$E(t) = -a\,i(t) + b.$$

By dividing both sides of the equation by $aE(t)$ we obtain the conductivity

$$\frac{i(t)}{E(t)} = \varkappa = e\mu n(t) = \frac{b}{aE(t)} - \frac{1}{a},$$

where $\varkappa$ is the conductivity, e the elementary charge, μ the mobility of the carriers of electricity in the sandwich, n their concentration, and a and b constants. If $E(t)$ decreases with time as shown for instance in Figs. 9, 10, 11, $\varkappa$ increases at the beginning of the first 40 minutes and the only quantity in the expression for the conductivity which can increase is n, i.e. the concentration of the carriers. On the other hand if $E(t)$ increases, as shown during the following 40 minutes in Figs. 9–12, the concentration of the carriers must decrease.

Atempts can be made to describe the variation of the concentration with time during the second 40-minute series after the flickering. With some approximations it can be assumed that both curves are exponential. In such a case

$$I(t) = (I_0 - I_\infty) e^{-ct} + I_\infty,$$

$$U(t) = (U_\infty - U_0)(1 - e^{-ct}) + U_0$$

and

$$\frac{I(t)}{U(t)} = \frac{I_0 e^{-ct}}{U_\infty (1 - e^{-ct})} + \frac{I_\infty}{U_\infty}$$

when assuming that $U_0 e^{-ct}$ may be neglected in the denominator.

The expression

$$\varkappa_\infty = k \frac{I_\infty}{U_\infty}$$

can be assumed to be a rest conductivity not related to the conduction mechanism present during the variations considered here. The conductivity determining these variations is then

$$\varkappa - \varkappa_\infty = k \frac{I_0}{U_\infty} e^{-ct} (1 - e^{-ct})^{-1}$$

or in the first approximation

$$e \mu n(t) = k \frac{I_0}{U_\infty} e^{-ct}.$$

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